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TITLE: EVALUATING THE PERFORMANCE OF PASSIVE-SOLAR-HEATED BUILDINGS

AUTHOR(S): J. Douglas Balcomb

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Los Alamos National Laboratory
Los Alamos, New Mexico 87545

# EVALUATING THE PERFORMANCE OF PASSIVE-SOLAR-HEATED BUILDINGS*

by

J. Douglas Balcomb
Los Alamos National Laboratory
Los Alamos, New Mexico 87545



ABSTRACT

Methods of evaluating the thermal performance of passive-solar buildings are reviewed. Instrumentation and data logging requirements are outlined. Various methodologies that have been used to develop an energy balance for the building and various performance measures are discussed. Methods for quantifying comfort are described. Subsystem and other special-purpose monitoring are briefly reviewed. Summary results are given for 38 buildings that have been monitored.

## INTRODUCTION

Beginning with the great upsurge of interest in passive solar buildings, which started in about 1975, obtaining performance data on actual buildings became a subject of great interest to the research community, the design community, and government program managers. The first monitoring of which we are aware was done by California Polytechnic State University on a roof pond house in Atascadero, California (1). Then, as now, the monitoring lent credibility to performance claims and provided valuable feedback to designers and analysts alike. Other early evaluations include the Wallasey School in England (2) and the Trombe-Michel house in France (3).

Since 1975 there have been a large number of individual passive solar buildings monitored and results reported. Approaches have varied widely, ranging from the large-sample monitoring done under the Class C program, which relies on utility bill data, weather station data, rough building dimensions, and occupant interviews, without use of monitoring instrumentation, to the incredibly detailed monitoring of the Class A program, where virtually everything of possible interest is measured.

This paper focuses on monitoring based on instrumented data. We make no attempt to comprehensively review all monitored buildings but instead to concentrate on the results and procedures of three specific efforts under which several buildings have been monitored. The purpose is to describe the various approaches taken to monitoring and, at the same time, to review enough buildings to give a general picture of the performance levels being achieved. The efforts reviewed are the following.

### Los Alamos National Laboratory

Much of the early monitoring work was done by Los Alamos in 15 different passive solar buildings, mostly in northern New Mexico (4). Because of the high cost of monitoring and limited available resources, much of this monitoring focused on specific passive solar elements. Detailed energy balances were performed on only four of the buildings. Even in these studies, the approach taken was slightly different in each case, tailored to the information available and the particular situation. This work was valuable primarily because it provided an early indication that passive solar buildings can work very well, gave some specific and unique information on several passive solar elements, and provided case histories of a variety of different monitoring approaches.

### National Solar Data Network (NSDN)

The NSDN was originally set up under the federal government program for monitoring active solar systems and was later expanded to include a few passive solar buildings. Information from an average of 90 sensors at each site is collected at a central evaluation facility by means of a telephone dial-up system. The analysis methodology was developed by the National Bureau of Standards and later refined by the system contractor, Vitro Laboratories. A very thorough and detailed comparative evaluation has been made of 11 passive solar buildings covered by this network for the 1980-81 heating season (5).

### Class B

This is the intermediate of three different monitoring efforts set up specifically for the passive solar program through the Solar Energy Research Institute (SERI) (6). Data from an average of about 20 sensors are fed to a microprocessor where performance measures are calculated on line and information is recorded locally on cassette tape. Although performance indices can be monitored locally, the bulk of the evaluation is done at SERI after the tapes have been collected and the data fed into a central computer system. Results from this program have just recently become available; in this paper we review results from the 1981-82 heating season for 12 buildings in Denver (7) and an additional 12 buildings in other parts of the US.

## INSTRUMENTATION AND DATA RECORDING

Instrumentation used for passive solar monitoring is relatively straightforward. Accuracy requirements are not especially high so that small, inexpensive, and convenient sensors can be used, such as thermocouples or solid state temperature probes. Ten or twenty temperature measurements are often sufficient to give an indication of temperature variations in various parts of the building and outside. Air temperatures are measured with shielded probes, and globe temperature is also sometimes recorded. Pyranometers are used to measure solar radiation, usually in the plane of the glazing and sometimes horizontal or behind the glazing. Electrical power is usually determined with watt-hour meters or by measuring line voltage and current using clip-on meters. Separate accounting is usually made for space heating, hot water heating, and total electric consumption. Fuel-fired heaters are calibrated and on-time is measured. Other measurements may include wind velocity and relative humidity. Status records are kept for movable insulation and other elements.

Although strip chart recorders have been used, normal practice today is to rely on automatic digital scanning and recording equipment. Data from frequent

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scans may be integrated and recorded at intervals ranging from 15 minutes to 1 hour.

## DIFFICULT MEASUREMENTS

Some energy flows in passive buildings are difficult to estimate, as outlined below.

### Energy Loss by Evaporation

Building energy loss by evaporation attributable to people, cooking, showers, and other normal activities is usually fairly small. However, in some passive solar buildings this loss is increased significantly by transpiration of water from plants, as might occur in a situation where a sunspace is used as a greenhouse. This may well increase the relative humidity in the house from the 10-20% level typical in winter to a more comfortable 40-60% level. Some of the energy associated with this evaporation may be recycled by condensation on the windows, but even this is probably re-evaporated. The energy loss due to evaporation can be measured indirectly knowing the inside and outside absolute humidities and the rate of air infiltration. In the case of the Balcomb house, we found that the transpiration rate so calculated was reasonably well correlated with sunspace temperature (8). The total energy associated with evaporation was estimated at 8% of the building load, far from negligible.

### Woodburning Stoves

These stoves are often used in passive solar buildings, and it would be improper and unnecessary to arbitrarily eliminate such buildings from monitoring. Efficiencies of woodburning stoves, as measured in many laboratory tests, vary no more widely than other fuel-burning appliances and are generally in the range of 50-65%. A reasonable approach to monitoring the output of woodburning stoves is to measure a surface temperature of the stove and to correlate this to the energy output, measured over a period of controlled burn in which the total weight of wood consumed is measured. We have found that the stove output is reasonably proportional to the difference between a stove surface temperature and the room temperature.

A more comprehensive approach was taken by Fowlkes (9), who measured wood consumption, air flow rates, and flue temperatures and was able to obtain an accurate stove calibration.

Woodburning fireplaces are quite a different matter. Efficiencies vary widely, and it is probably not practical in a normal monitoring program to make a reasonable estimate of the fireplace contribution. If a fireplace is present, it is prudent to make a temperature measurement in the vicinity to determine whether or not the fireplace has been used. This information may be useful in explaining anomalies.

### Vented Energy

During periods when heat losses are small and solar gains are high, the occupants of the building will vent energy by cracking open windows or doors. This energy loss is in excess of that associated with the normal infiltration expected when the building is closed. Venting occurs, to a greater or lesser extent, in virtually every passive solar building during the spring and fall seasons. It is virtually impossible to measure, although the position of windows and doors can be monitored with switches. Vented energy can be inferred by subtraction if other energy quantities are known.

### People Heat

Heat from people is typically 10-20% of the internal gains and is normally estimated with sufficient accuracy based on typical occupancy patterns.

### Heat Losses to the Ground

These energy exchanges are very difficult to determine. Probably the most useful estimates can be made by measuring temperature gradients in concrete walls or floors adjacent to the earth.

### Heat Storage in Building Materials

This is a transient effect and it is not necessary to evaluate it if only long-term results are desired. However, a thorough monitoring will seek to determine the effectiveness and time duration of heat storage in various mass elements in the building (10). This can be done by measuring the temperature histories of the various materials. Accurate estimates of heat fluxes can be made based on temperatures measured at three depths within the material using the diffusion equation (11). The major difficulty with these measurements is that a large number of temperature measurements must be made to obtain a comprehensive picture.

## ENERGY BALANCE METHODOLOGY

### Determining the Heat Loss Coefficient

Nearly all monitoring analysis assumes that building losses can be characterized by a heat loss coefficient; the product of this heat loss coefficient times the inside/outside temperature difference yields the rate of heat loss from the building. This heat loss coefficient can be calculated by conventional methods using handbook values or manufacturer's data for the conduction coefficients of the various building exterior surface elements and the area of each element. The biggest unknown in this process is determining the rate of air infiltration.

It is strongly recommended that the heat loss coefficient should be measured rather than relying solely on calculated values. The procedure used by the Class B program is to perform a one time coheating test of the building during which inside temperatures are held constant using electric heaters and all solar gains are defeated by covering the windows. The heat loss coefficient can then be determined by dividing the measured energy input by the integral of the inside/outside temperature difference over a time interval during which the temperatures of heat storing materials in the building are held constant.

The procedure used by Fowlkes and Balcomb was to determine the heat loss coefficient over a period of a week or more accounting explicitly for the solar gains. Fowlkes measured the solar gains using a pyranometer located behind the glazing (9). Balcomb and Hedstrom calculated the solar gains through each of the six glazing orientations in the building based on the measured horizontal solar radiation (12). The procedure involved separating the solar radiation into direct and diffuse and determining the total solar gain as the sum of calculated diffuse, reflected, and direct components as a function of the angle of incidence. By using a long measurement period, the effect of heat storage in the building can be minimized, although this was accounted in a first-order way based on observed differences of the major mass temperatures from the beginning to the end of the measurement period.

The Class B system uses a one time measurement of the air leakage area of the building by means of a blower door test; the infiltration losses are then calculated using the inside/outside temperature difference and wind velocity according to techniques devised by the Lawrence Berkeley National Laboratory. The results of the coheating test are then used to determine the conduction portion of the heat loss coefficient. In most cases, measured values of heat loss coefficient agree reasonably well (± 20%) with calculated values.

### Use of the Energy Balance

In almost all monitoring evaluation, it is assumed that an energy balance must be achieved. This means that the sum of all energy sources minus losses must equal the heat stored in the building within the time period. The most common practice, adopted by both the NSDN and Class B, is to use an energy balance to infer solar gains. Using this procedure, solar radiation into the building is not measured directly but is determined by subtraction, knowing all other energy terms. This is a somewhat questionable procedure because it means that errors made in determining the heat loss of the building translate directly into errors in calculated solar gains.

If the subtractive method is used, it must be realized that the energy term that is calculated is actually an energy residual and accounts for the net effect of both solar gains and any losses over and above those associated with the measured heat loss coefficient. The most significant unaccounted effect is the energy released from the building by intentional venting. This effect can be significant. Vented energy was determined in the Balcomb house using a subtractive technique in which solar gains and evaporation losses were estimated using the procedures outlined above. The magnitude of venting was found to be small during the midwinter months of December, January, and February, but accounted for 11% of the total energy loss of the house over the 6-month period from November through April (12). Failure to account for this vented energy, which is essentially unmeasurable by any direct means, does not tend to bias the final results as regards the overall performance of the building, but may significantly alter interpretation of the collection efficiency of the solar glazing.

Our recommendation is that solar gains should be determined directly rather than by subtraction, using a combination of measurement and analysis to determine the total solar gains transmitted through all windows. This may require the measurement of solar radiation in more than one plane to obtain sufficient accuracy.

## PERFORMANCE MEASURES

Each of the calculated energy terms is usually integrated over periods of 1 day, 1 month, and the season. The major categories are auxiliary heat, total building load, stored energy, internal gains, measured or inferred solar gains, and other energy quantities that may be determined in a particular situation.

Quite a variety of performance measures have been developed by various evaluation groups, and one must be careful to note the exact definition of terms. The performance of a building depends on the weather, the building design, and the manner in which the building is operated. It is very difficult to separate these three effects so as to single out information on the effectiveness of the building design.

The most simple and straightforward performance measure is the amount of auxiliary that is used. This measure is often normalized to the heating degree days during the measurement period to provide a first-order correction for climate. This procedure, of course, does not give any weight to the fact that one building may receive considerably more sun than another, that one occupant may maintain the inside temperature at a higher level than another, or that an occupant might increase heat losses by an inordinate number of door or window openings.

Perhaps the most comprehensive study of various performance measures has been made by the NSDN in a comparative analysis of the performance of 11 passive solar heated buildings (5). Many different ways of comparing the results are explored, including different ways of normalizing the auxiliary heat requirements. Although useful, none of these approaches can fully remove the effects of weather or occupants.

It is recommended that in reporting the data at least the following quantities be given.

### Building Load Coefficient

This is the heat loss of the building per unit of inside/outside temperature difference; it is often normalized to the building floor area. It provides an indication of how well conservation has been implemented in the design.

### Building Load

This is the product of the building load coefficient times the actual degree hours for the evaluation period. It gives a direct indication of the energy requirement of the building. It is also instructive to determine a useful building load defined as the energy required to maintain building temperatures at the thermostat setpoint. Energy that heats the building above the thermostat setpoint is not counted. Some degree of overheating may be welcome by the building occupants, although a major amount would be viewed as a liability; in any case, this excess energy is not required and thus does not add to energy savings.

### Internal Heat

This is all energy from lights, appliances, people, and equipment other than intentional backup heating.

### Auxiliary Heat

This is perhaps the most critical performance measure. It is useful to normalize it to the building floor area and also to the heating degree days, calculated for the actual conditions at the site.

### Average Inside Temperatures

### Average Outside Temperature

### Solar Radiation

The total solar radiation incident on the collection glazing is useful for normalizing the solar gains and solar savings.

### Solar Gains

This quantity is determined either by the subtractive method or preferably by measurement and analysis.

### Solar Savings

This is the useful building load minus the internal gains (assumed to be useful) minus the auxiliary heat. This is presumably the additional auxiliary heat that would have been required in the absence of solar gains. It is useful to normalize this quantity for the season to the glazing area and also to normalize it by the total incident solar radiation to determine a useful efficiency.

The above list does not include a solar fraction. Solar fractions are not of primary interest but are usually reported anyway. They are useful in giving an indication of the proportion of the total building load that is supplied by solar gains.

The presence of the solar glazing increases the building load coefficient and thus the building load. It is very useful in reporting results to distinguish which portions of the building load are associated with solar glazing and which are not. If these losses are subtracted from the useful building load, it is possible to determine a more meaningful comparison load. In the terminology of Ref. 13 this measure is called a net building load as distinct from the gross building load, which includes losses through the solar glazing. The solar glazing load can be determined from the integral of the measured inside/outside temperature difference and the loss coefficient of the glazing system. If movable insulation is used, it is important to know the actual schedule and to estimate the effective loss coefficient of the glazing system with the movable insulation in place. This amount may be less than the predicted value, as was observed by Fowlkes.

Thermal Comfort Issues

Because an objective of passive solar heating is to provide thermal comfort, it is important to report the extent to which this has been accomplished. Thermal comfort is normally treated very superficially in performance evaluations. A very useful method of displaying this information is shown in Fig. 1, which indicates the frequency distribution of temperatures measured in a particular location identified by day and nighttime intervals. A useful corollary is to calculate the discomfort index for this same measurement as suggested by Carroll (14). This index is determined in a manner so as to be roughly proportional to human discomfort. Measurements should be made and reported for each thermally distinct zone of the building.

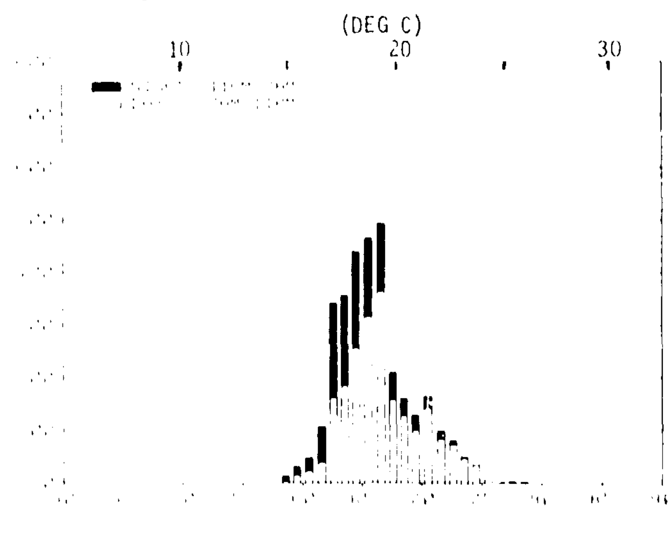


Fig. 1. Room temperature history in the Hunn house, November 1, 1978, through April 16, 1979. The number of hours of occurrence in each 0.55°C temperature band (1°F) are shown. The white and black portions of the bar show whether the hours occurred during the day (7:00 a.m. to 11:00 p.m.) or at night (11:00 p.m. to 7:00 a.m.).

COMPONENT EVALUATIONS

It is often possible to monitor and evaluate the performance of a specific element or component of a building without attempting to understand energy flows in the rest of the building. This information can be very useful and is less expensive to obtain than a complete evaluation.

One example is the evaluation of the Trombe wall in the Hunn residence (15). By measuring temperatures in the wall and solar radiation, it was possible to calculate heat fluxes into and out of the wall and to determine the overall wall efficiency. The results are shown in Fig. 2. This type of information is very useful in determining how improvements in performance may be made by identifying the major losses. Subsequently, an overall energy balance of the building was also developed.

Component monitoring can also be done in test rooms (16). The advantage is that the overall energy production of the component can be checked; the accuracy obtained is usually greater.

OVERVIEW OF SOME RESULTS

Some results from 38 monitored buildings are given in Fig 3. Building descriptions are outlined in Table 1. Because we cannot hope to provide a comprehensive review in this short paper, the reader should consult source documents for more information. The parameter plotted in Fig. 3 is energy, normalized by dividing by the building floor area and by the actual heating degree days. The total length of the bar from top to bottom is a measure of the total heat loss coefficient. The buildings are arbitrarily rank ordered according to auxiliary energy (the black portion of the bar above the zero line). The white portion shows the solar energy contribution, determined by the subtractive method. Internal heat is the black portion of the bar below the zero line. Four buildings were unoccupied, as noted. Harrop had the thermostat set back so that it cannot be fairly compared with the others, although it is clearly a good performer. Insufficient information was available for most of the buildings to determine useful loads, solar savings, and thermal comfort.

CONCLUSIONS

The picture that emerges from monitoring and evaluation leads to the following conclusions:

- Building heat load coefficients in the range of 0.83 to 1.53 W/°C m² (3.5 to 6.5 Btu/°F day ft²) are routinely achieved, although much larger values are observed for a few buildings. The results underline the importance of good conservation practice.

- Auxiliary heating requirements as low as 0.24 to 0.48 W/°C m² in sunny climates (1 to 2 Btu/°F day ft²) are quite achievable. Values of 1-1/2 times these levels are quite routinely achieved.

- Good overall performance is not especially correlated with climate, although there is some tendency for the solar performance to be better in sunny climates.

- Internal heat varies widely and in some cases makes a major contribution.

- Solar fractions of 50% or greater are often achieved. In some cases, notably Site NEA, Site MAM, Site MAC, and Modena, the solar performance is illusory because losses from the glazing probably equal or exceed solar gains. It is estimated that the solar savings exceeds 50% of the net load in 17 of the 38 buildings.

- Other benefits should also be considered. For example, the daylighting benefit in the Taos

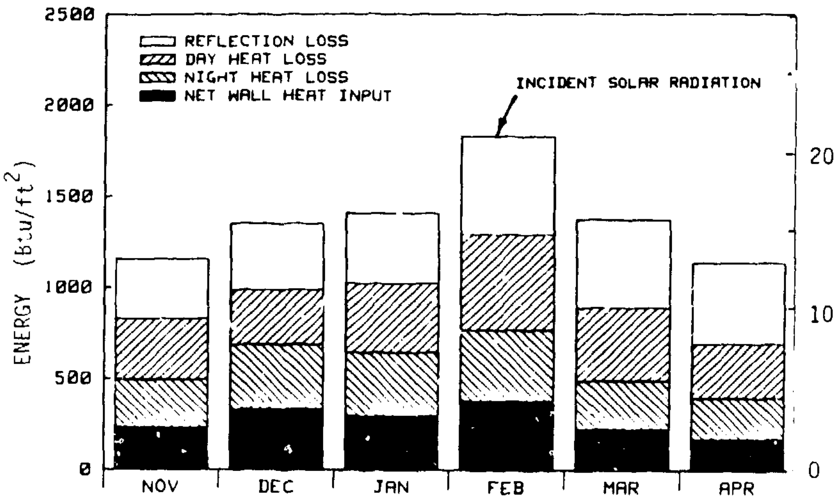


Fig. 2. Hunn house Trombe wall performance, November 1, 1978, to April 16, 1979. Relative to the total incident solar radiation (top of bar), the wall delivered heat to the adjacent space (black portion) with a seasonal efficiency of 20%. Transmittance losses are 22% (could be reduced by higher transmittance glazing), night losses are 23% (could be greatly reduced by night insulation), and the combined night and day losses are 58% (could be reduced by low-loss glazing or by a selective surface).

State Office Building reduces the need for artificial lighting by at least 60%. This explains the moderate internal heat observed, which is very low for an office.

- Proper site selection and passive collector orientation are very important to good performance. Some systems demonstrating the worst performance are those that are sited incorrectly.
- Movable insulation can notably improve performance and is especially valuable in colder climates. However, if manually operated movable insulation is used, it must be convenient and easy to use, reliable, and kept in good working order.
- No particular passive system type emerges as the best performer. Good thermal design, however, is essential.
- The overall need for purchased energy is far less than that of typical buildings in all but two of the 38 buildings included in Fig. 3.
- Many valuable lessons can be learned from a thorough review of monitored building data. Although not detailed here, both positive and negative factors, which could be reinforced or solved by better design, are uncovered in virtually every instance.
- An important deficiency of monitoring is the determination and reporting of the quality of the indoor environment created. Comfort indices should be given. Also, lighting, humidity, ambiance, and convenience should be evaluated.

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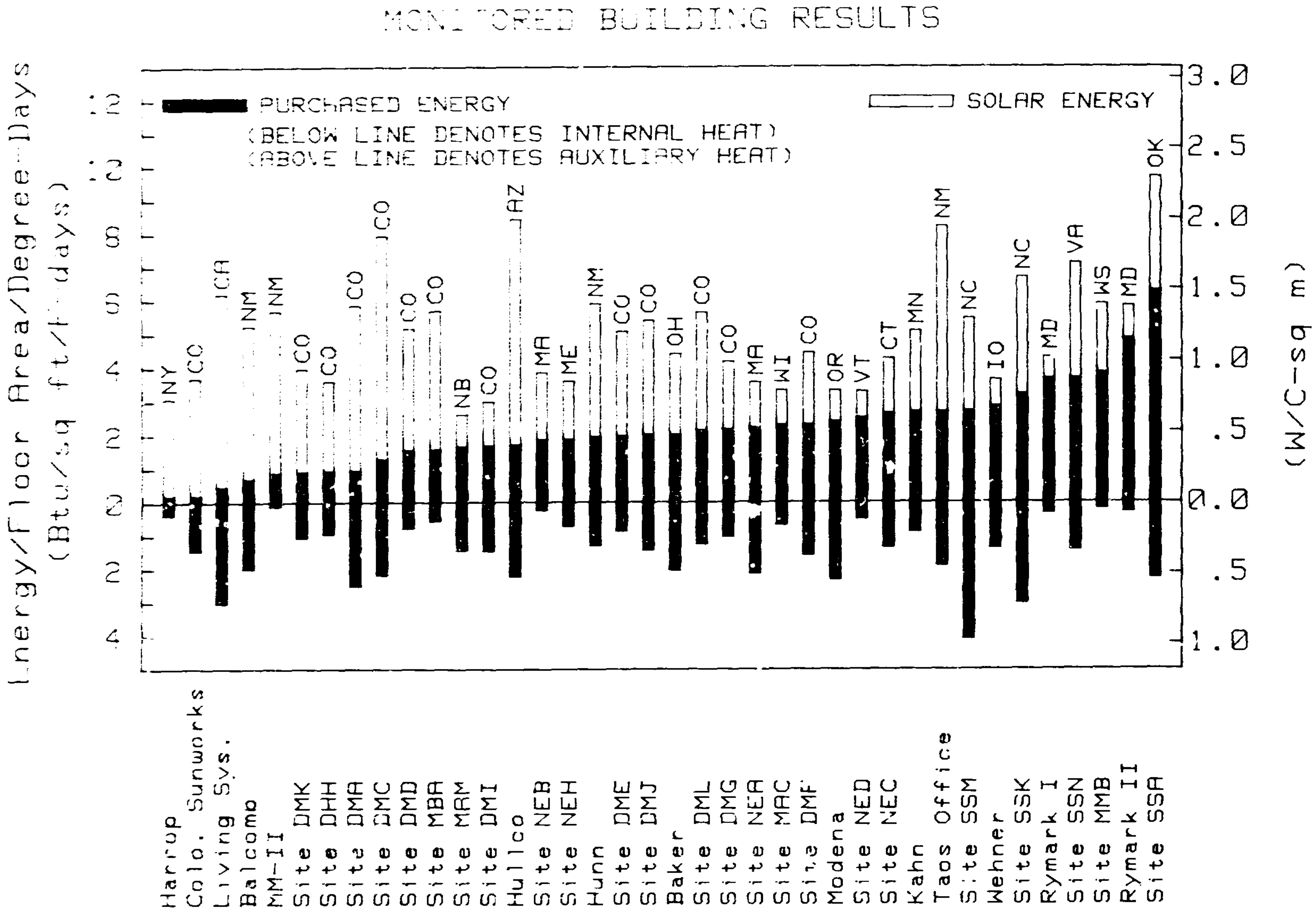


Fig. 3. Results of the monitoring of several buildings listed in Table 1. The bars show seasonal energy (usually for 5 or 6 months) divided by the building floor area and the actual degree days for the season, calculated for a base temperature of 18.3°C (65°F). The black portion of the bar denotes purchased energy; the portion below the bar is internal energy, and the black portion above the bar is auxiliary heat. The total length of the bar is the total heat required by the building, determined using the building heat load coefficient and the measured inside/outside $\Delta T$ integral. Thus, by subtraction, the white portion of the bar is the solar energy absorbed less any vented energy. The state in which the site is located is indicated above the bar. The buildings are rank ordered according to auxiliary heat. Note that the Harrop house had the thermostat set at a low level; thus it cannot be fairly compared with the others. Several other buildings with low internal heat were unoccupied but were thermostatically controlled to normal levels.

TABLE I

MONITORED PASSIVE SOLAR BUILDINGS

| Identification | Location | Type* | NI** | Organi-zation | Floor Area m² | (ft²) | Glazing Area m² | (ft²) | Ratio*** |
|---|---|---|---|---|---|---|---|---|---|
| Site DML | Denver,CO | DG | | Class B | 142 | (1527) | 15 | (161) | .11 |
| Site DMI | Denver,CO | DG | | Class B | 241 | (2590) | 25 | (264) | .10 |
| Site DMD | Denver,CO | DG | NI | Class B | 262 | (2820) | 34 | (365) | .13 |
| Site DMA | Denver,CO | SS/HY | | Class B | 157 | (1684) | 26 | (279) | .17 |
| Site DHH | Denver,CO | SS/HY | | Class B | 128 | (1376) | 14 | (149) | .11 |
| Site DMF | Denver,CO | DG/HY | | Class B | 174 | (1873) | 27 | (286) | .15 |
| Site MBA | Denver,CO | DG | NI | Class B | 221 | (2375) | 26 | (284) | .12 |
| Site DMJ | Denver,CO | DG | | Class B | 121 | (1298) | 13 | (140) | .11 |
| Site DMG | Denver,CO | SS/TW | NI | Class B | 235 | (2531) | 29 | (307) | .12 |
| Site DMC | Denver,CO | DG | | Class B | 126 | (1360) | 16 | (167) | .12 |
| Site DMF | Denver,CO | SS/LG | | Class B | 301 | (3236) | 41 | (426) | .13 |
| Site DMK | Denver,CO | TW | | Class B | 166 | (1784) | 32 | (339) | .19 |
| Site NEA | Hamilton,MA | DG | NI | Class B | 195 | (2100) | 37 | (403) | .19 |
| Site SSK | Black Mt.,NC | TW/DG | | Class B | 86 | (927) | 8 | (88) | .09 |
| Site SSM | Carrboro,NC | DG | | Class B | 152 | (1632) | 23 | (244) | .15 |
| Site SSA | Edmond,OK | DG/HY | | Class B | 223 | (2400) | 41 | (440) | .18 |
| Site NEH | Topsham,ME | SS/DG | NI | Class B | 143 | (1540) | 18 | (193) | .13 |
| Site SSN | Richmond,VA | WW/DG | | Class B | 115 | (1236) | 24 | (261) | .21 |
| Site MAM | Lincoln,NB | SS/HY | | Class B | 260 | (2800) | 35 | (380) | .14 |
| Site NEB | Orange,MA | SS/DG | NI | Class B | 125 | (1342) | 19 | (208) | .15 |
| Site MAC | Eau Claire,WI | DG/SS | NI | Class B | 168 | (1812) | 32 | (343) | .19 |
| Site NED | Newport,VT | DG | | Class B | 130 | (1400) | 8 | (89) | .06 |
| Site NEC | Tolland,CT | SS/DG | NI | Class B | 188 | (2028) | 21 | (224) | .11 |
| Site MMB | Marshfield,WS | DG | | Class B | 88 | (946) | 8 | (86) | .09 |
| Harrop | Big Flats,NY | DG | NI | NSDN | 126 | (1360) | 37 | (403) | .30 |
| Rymark I | Frederick,MD | DG | | NSDN | 149 | (1600) | 8 | (84) | .05 |
| Rymark II | Frederick,MD | DG | NI | NSDN | 149 | (1600) | 15 | (160) | .10 |
| Colo. Sunworks | Longmont,CO | WW/DG | NI | NSDN | 173 | (1863) | 36 | (382) | .21 |
| Living Sys. | Davis,CA | WW/DG | NI | NSDN | 158 | (1700) | 25 | (273) | .16 |
| Modena | Eugene,OR | WW/DG | NI | NSDN | 139 | (1500) | 20 | (210) | .14 |
| Taos Office | Taos,NM | WR/DG | NI | NSDN | 1115 | (12000) | 291 | (3126) | .26 |
| Wehner | Iowa City,IO | DG/WW | NI | NSDN | 156 | (1700) | 26 | (277) | .16 |
| Baker | Cincinnati,OH | SS/HY | | NSDN | 149 | (1600) | 32 | (347) | .22 |
| Hullco | Prescott,AZ | SS/HY | | NSDN | 98 | (1050) | 39 | (424) | .40 |
| Kahn | Duluth,MN | DE | | NSDN | 232 | (2500) | 50 | (538) | .22 |
| Balcomb | Santa Fe,NM | SS/HY | | Los Alamos | 181 | (1950) | 38 | (407) | .21 |
| Hunn | Los Alamos,NM | TW/DG | | Los Alamos | 182 | (1955) | 35 | (373) | .19 |
| MM-II | Los Alamos,NM | WR/DG | NI | Los Alamos | 101 | (1090) | 45 | (479) | .44 |

*Types are: DG, direct gain; SS, sunspace; TW, Trombe wall; HY, hybrid; WW, waterwall; DE, double envelope; WR, water roof.

**Systems with some movable night insulation designated NI.

***Ratio of net glazing area to gross floor area.


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